Search for Monoenergetic Positron Emission from Heavy-Ion Collisions at Coulomb-Barrier Energies

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Positron production in ^{238}U + ^{232}Th and ^{238}U + ^{181}Ta collisions near the Coulomb barrier has been studied. Earlier experiments reported narrow lines in the spectra of positrons, accumulated without the requirement of electrons detected in coincidence. No evidence of such structure is observed in the present data. The positron energy spectra are compared with estimates from dynamic atomic processes, and from internal pair conversion of electromagnetic transitions from the excited nuclei. [S0031-9007(96)02277-6]

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Positron production in the collisions of very heavy nuclei at Coulomb-barrier energies has attracted a great deal of attention over the past 15 years. This process is of particular interest since the positron production mechanism is intimately linked to the very strong electromagnetic fields which occur in these collisions. These fields become "supercritical" when the united charge of the two ions (Z_U) is greater than approximately 173, and when the nuclei approach to within approximately 100 fm [1]. This phenomenon has been previously investigated in a number of experiments (e.g., [2,3]). In later experiments with $Z_U = 180$ to 188, the energy spectra of positrons displayed unexpected narrow structures at energies near 300–400 keV, with widths of 60 to 80 keV. The initial observation of such peaks in the ^{238}U + ^{248}Cm system ($Z_U = 188$) [4] prompted the suggestion that they might be related to the spontaneous production of positrons associated with the overcritical binding of vacant electron orbitals in a relatively long-lived quasiatomic system. The analysis of data from subsequent experiments, however, showed evidence for similar structures in a number of other systems, with characteristics which were inconsistent with the expectations for the spontaneous production mechanism [5]. In particular, the expected very strong Z_U dependences of the peak energy and yield ($\propto Z_U^N$ where $N \approx 20$) were not observed.

Structures were also observed in a different set of measurements for the ^{238}U + ^{238}U and ^{238}U + ^{232}Th systems [6,7]. While the energies of the peaks in these data were lower, the general features appeared to be similar to those described previously. In particular, the narrow widths of the lines were taken to imply that the source velocities in the laboratory frame were relatively low, close to that of the center-of-mass of the colliding heavy ions. Finally, weaker evidence has been reported for peaks in subcritical ($Z_U < 173$) systems, including ^{238}U + ^{181}Ta ($Z_U = 165$) [8].

The characteristics of these structures suggested that their source might be the decay of a light neutral particle X_0 into a positron-electron pair, which would lead to almost monoenergetic positrons of kinetic energy $E_{e^+} \approx (m_{X_0} - 2m_e)c^2/2$. Sharp sum-energy lines consistent with this hypothesis have been reported in positron-electron coincidence spectra, from collisions in the ^{238}U + ^{232}Th system [9,10]. In recent measurements by our collaboration [11] and others [12], however, these coincidence lines have not been reproduced. Here we report an analysis of the positron energy spectra obtained without the requirement of coincident electrons for collisions in the ^{238}U + ^{232}Th and ^{238}U + ^{181}Ta systems. These data represent a search for features related to those which originally motivated the more difficult positron-electron coincidence measurements, and which complement the data presented in [11].

The measurements utilized the ATLAS positron experiment (APEX) apparatus [11,13]. This apparatus has efficiency comparable to or greater than that of the spectrometers used in the earlier studies. The experiment was carried out using the 100% duty cycle ^{238}U beams available from the ATLAS accelerator at Argonne National Laboratory. Typical beam intensities ranged from 2 to 4 particle nA.

The APEX spectrometer [13] consists of a magnetic transport system utilizing a large volume solenoid with its axis aligned perpendicular to the beam direction. The positrons produced in the ^{238}U + ^{232}Th and ^{238}U + ^{181}Ta collisions are transported in this field to one of two highly segmented arrays of silicon detectors positioned on the solenoid axis. Positrons are identified and distinguished from electrons by detection of their characteristic 511 keV annihilation radiation using cylindrical assemblies of position-sensitive NaI crystals which surround the silicon arrays. These detectors measure the energy of each photon and its detection position. The resulting geometrical information provides excellent suppression of background in the positron signal. The spectrometer can detect positrons that have kinetic energies between approximately 150 and 1000 keV, and is optimized for positron energies between 250 and 750 keV. The acceptance of the device admits positrons emitted at polar angles relative to the solenoid axis ranging from 20° to 70°. Two ionization counters, and two CsI crystals installed at 11° relative to the beam axis, provide detailed information on the target thickness and condition, as well as on the instantaneous beam intensity and beam-spot position. A 70% relative efficiency high purity intrinsic Ge detector was used to obtain gamma-ray spectra.

For the ^{238}U + ^{232}Th system, rolled metal foils of areal density 700 to 800 μg/cm^2 were mounted on a rotating wheel mechanism to reduce deterioration under beam exposure. The more robust Ta targets were of areal density 600 to 800 μg/cm^2. These targets were kept stationary, except that their positions were changed approximately every 2 h, when the elastic scattering peak yields measured in the monitor detectors indicated that the target thickness had diminished by $\approx$10%. Experimental parameters, including average beam energies, target thicknesses, integrated luminosities, and total numbers of positrons identified for data sets obtained at E_{beam} = 5.95, 6.10, and 6.30 MeV/nucleon for the ^{181}Ta target, and at E_{beam} = 5.95 MeV/nucleon for the ^{232}Th target are given in Ref. [11].

The energy spectra of positrons detected in coincidence with two heavy ions scattered to laboratory angles between 20° and 68° are shown in Fig. 1. In each case, the spectrum is smooth, with a shape that largely reflects the energy acceptance of the APEX spectrometer. The dotted lines represent the expected yield arising from a combination of internal pair conversion (IPC) of high-energy nuclear transitions, following Coulomb excitation or transfer reactions, and positrons produced by the strong, time-varying electromagnetic fields which occur during the collision ("dynamic" positrons). The IPC portion of the theoretical positron yield was based on gamma-ray spectra obtained at the same time as the positron measurement, and calculated using a multipolarity decomposition of the gamma-ray cross section as described in Refs. [14,15] and pair conversion coefficients from Ref. [16]. The gamma-ray spectra above 1 MeV are dominated by a smooth continuum, with discrete transitions making up no more than a few percent of the yield. The contribution to the positron spectrum from dynamic atomic processes was obtained from the results of calculations using a coupled-channels model of the scattering reaction [17–19]. As an example, the theoretical positron spectrum with its contributing components for the ^{238}U + ^{232}Th system at E_{beam} = 5.95 MeV/nucleon, before correction

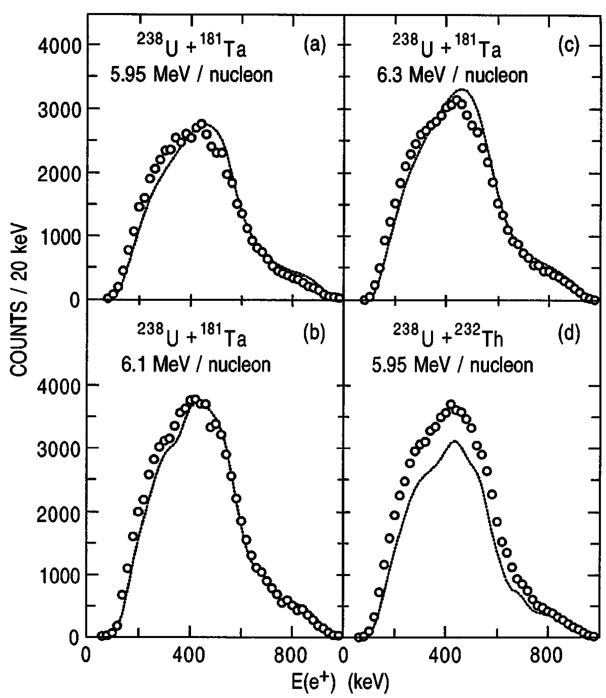

FIG. 1. Positron energy spectra for ^{238}U +^{181} Ta scattering at E_{lab} = (a) 5.95, (b) 6.10, and (c) 6.30 MeV/nucleon, and (d) ^{238}U + ^{232}Th at E_{lab} = 5.95 MeV/nucleon. The data were collected in coincidence with two detected heavy ions. The data and calculated curve in (d) are multiplied by 1/3. The dotted curves in (a)–(d) are discussed in the text.

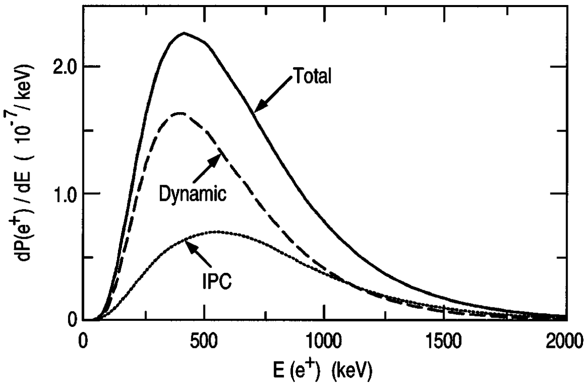

FIG. 2. Calculated positron energy spectrum for ^{238}U + ^{232}Th at 5.95 MeV/nucleon, before correction for response of the APEX spectrometer. The dashed (dotted) curve represents the contribution from dynamic (nuclear) processes.

for the response of the apparatus, is shown in Fig. 2. No normalization factors have been applied to the calculated spectra which appear in Fig. 1.

The response of APEX has been calculated using the Monte Carlo code GEANT, and includes geometrical effects of transport of positrons in the magnetic field, backscattering and incomplete lepton energy loss in the silicon wafers, and incomplete light collection in the NaI detectors. The results of this simulation can adequately reproduce the measured response of the spectrometer to positrons and electrons emitted from radioactive sources, as has been illustrated in Ref. [13].

For the ^{238}U + ^{181}Ta case, where the positron yield is dominated by IPC, the theoretical estimates are in excellent agreement with the data at all beam energies. For the ^{238}U + ^{232}Th system, where it is expected that more than 75% of the positrons are produced by dynamic processes, the data exceed the theoretical estimate by approximately 20%. This result may indicate that the dynamic positron yield is enhanced compared to the theoretical prediction in the ^{238}U + ^{232}Th system, although this level of agreement between theory and experiment is comparable to that achieved previously [5–7]. Substantially larger enhancements of the dynamic yield above theory have also been reported [20]. The total measured positron production cross sections for energies between 250 and 750 keV, and laboratory heavy-ion scattering angles between 25°and 65°, are given in Table I, as is the deduced decomposition of the cross section into contributions from nuclear and dynamic processes. The errors quoted are dominated by systematic uncertainties in the deconvolution of the APEX response, the detection efficiency of the heavy-ion counter array, and in the assumptions made for the multipolarity distribution for the gamma rays contributing to the nuclear positron yield.

For the ^{238}U + ^{232}Th system, we observe no narrow structures in the spectrum at energies where peaks were previously reported, from 280 to 350 keV [5–7], nor at any other energy in the spectrum. The cross sections for peaks in the ^{238}U + ^{232}Th system were previously reported to range from $d\sigma_{e^+}/d\Omega_{\mathrm{HI}} \approx 6$ μb/sr between $\theta_{\mathrm{HI}}(\mathrm{lab}) =$ 12° and 51° [7], to $\approx$10 μb/sr, between $\theta_{\mathrm{HI}}(\mathrm{lab}) = 50°$ and 65° [5]; here $d\sigma_{e^+}/d\Omega_{\mathrm{HI}}$ is the positron production cross section per unit center-of-mass solid angle of the scattered heavy ion [5–7]. Assuming isotropic peak positron emission in the heavy-ion center-of-mass frame, both of these estimates correspond to an angle-integrated peak cross section between 30–50 μb. There is conflicting evidence in earlier publications on the dependence of the peak yield upon the kinematics of the heavy-ion reaction. Whereas in Refs. [4] and [5] the peak was reported to be strongly enhanced by selection of heavy-ion scattering angles between 50° and 65° in the laboratory, a plot of peak cross section versus angle given in Ref. [7] shows only a very weak scattering-angle dependence. To investigate these possibilities we have sorted the ^{238}U + ^{232}Th positron data according to several different heavy-ion scattering-angle ranges. Because of the near-symmetric nature of the system, the ranges chosen contain contributions from both forward and backward angles in the heavy-ion center-of-mass system.

For comparison with the published data, Fig. 3 shows positron energy spectra selected on heavy-ion scattering angles corresponding to those described in [6,7] [Figs. 3(a)–3(c)], and [4,5] [Fig. 3(d)]. Here, the positron data are displayed with the energy in the laboratory frame [Fig. 3(a)], as well as corrected for the kinematic shift assuming emission from the heavy ion center-of-mass frame [Fig. 3(b)]. For further comparison with the results of [6,7], Fig. 3(c) shows a positron energy spectrum containing events where both the heavy-ion and positron emission angles correspond to those described in [6,7]. None of these spectra show any evidence for peaks similar to those previously reported between $250 \leq E_{e^+} \leq 400$ keV. A variety of other cuts of the data on heavy-ion kinematics have also been performed, none of which lead to spectra with any statistically significant indications of structures such as those observed in earlier measurements. For comparison, lines with energies and widths comparable to those described in the literature have been generated, with total cross sections of 50 μb [7] for Figs. 3(a) and 3(c), and 30 μb [5] for Fig. 3(d), in all cases assuming uniform production throughout the target. The differences in the overall positron yield, and the peak yields, arise from the different ranges of heavy-ion and positron solid angle considered. In each case, the ratios of calculated signal to measured continuum are similar to the experimental peak to background ratios shown in Refs. [5,7], and such a signal should be observable in our data.

In conclusion, we have studied the production of positrons from collisions of ^{238}U + ^{181}Ta and ^{238}U + ^{232}Th nuclei, at energies near the Coulomb barrier. A comparison of the continuum yields with calculations of the contribution of IPC and dynamic quasiatomic processes

TABLE I. Positron production cross sections integrated between $250 \leq E(e^+) \leq 750$ keV.

System	Beam energy range (MeV/nucleon)	$\sigma_{e^+\mathrm{MEAS}}$[a] ($\mu$b)	$\sigma_{e^+\mathrm{IPCS}}$[b] ($\mu$b)	$\sigma_{e^+\mathrm{DIF}}$[c] (μb)	Theory $\sigma_{e^+\mathrm{DYN}}$[d] (μb)
^{238}U + ^{181}Ta	5.79–5.95	680	530	150(60)	131
^{238}U + ^{181}Ta	5.94–6.10	710	470	240(60)	188
^{238}U + ^{181}Ta	6.13–5.95	910	660	250(80)	241
^{238}U + ^{232}Th	5.78–5.95	1660	400	1260(90)	876

[a]Experimental e^+ cross section corrected for APEX acceptance. Systematic uncertainties estimated to be ±5%.
[b]IPC yield estimated from gamma-ray spectra as described in the text. Systematic uncertainties estimated to be ±10%.
[c]Experimental "dynamic" positron cross section calculated from $\sigma_{e^+\mathrm{DIF}} = \sigma_{e^+\mathrm{MEAS}} - \sigma_{e^+\mathrm{IPC}}$.
[d]Theoretical "dynamic" positron cross section from [17–19].

shows that the calculations are in good qualitative agreement with the data. In the case of the ^{238}U + ^{232}Th system, where previously narrow lines have been reported in the positron energy spectra, no such structures are present in our data, whether or not selections are made on the data based on heavy-ion scattering parameters. The 99% confidence level upper limits for the presence of such a peak in our ^{238}U + ^{232}Th data, calculated by searching for 60 keV FWHM deviations from smooth behavior in the measured spectrum, correspond to a 1–2 μb total production cross section assuming that the positron peak yield is independent of heavy-ion scattering angle. For the more restrictive case where the peak is assumed to arise from a narrow range of scattering angles as suggested in [5], the upper limits are also between 1 and 2 μb. These limits are to be compared with the 30–50 μb total cross sections for positron peaks reported previously. This discrepancy is particularly interesting in light of the absence of lines in recent e^+-e^- coincidence data [11,12].

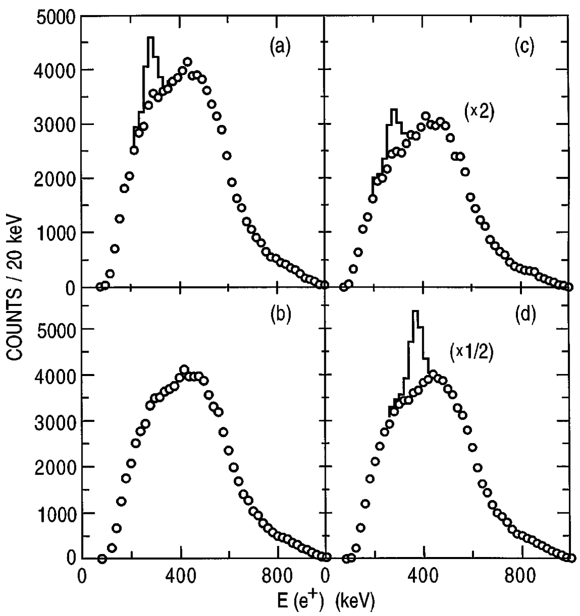

FIG. 3. Positron energy spectra from ^{238}U $+^{232}$ Th collisions at $E_{\mathrm{lab}} = 5.95$ MeV/nucleon selected on different heavy-ion scattering-angle ranges. (a) APEX e^+ acceptance, $\theta_{\mathrm{HI}}(\mathrm{lab}) = 25°–32°$. (b) APEX e^+ acceptance, $\theta_{\mathrm{HI}}(\mathrm{lab}) = 25°–32°$, e^+ energy corrected for kinematic shift to the heavy-ion center-of-mass frame. (c) e^+ detected with polar angles 30°–70° with respect to the beam axis, $\theta_{\mathrm{HI}}(\mathrm{lab}) = 25°–32°$, (d) APEX e^+ acceptance, $\theta_{\mathrm{HI}}(\mathrm{lab}) = 50°–65°$. The data in (c) are multiplied by 2, and those in (d) by 1/2. The calculated signals are discussed in the text.

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